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Effect of Reduced Data Resolution on Reconstruction Accuracy of Aircraft States and Winds Along the Flightpath

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SUMMARY

This report focuses on the resolution of the digital flight data recorder measurements that are used to reconstruct time histories of the aircraft state and flightpath winds (winds along the flightpath). A sensitivity analysis is performed to determine the effects of reduced data resolution on state and wind reconstruction. Three different data sets that represent three different modes of flight are used in this analysis. Two sets are from actual digital flight data recorders; the third is simulated. Estimates of aircraft inertial velocity and flightpath-wind velocity computed from the data sets make up the nominal solutions. The resolution of each data channel used in the nominal solutions (three Euler angles, three air-data variables, and three components of translational body acceleration) is then systematically reduced and the solutions are recomputed. The RMS error between the nominal and reduced-resolution aircraft-velocity and wind-velocity solutions quantifies the effect of reduced resolution. Graphs showing RMS error versus measurement resolution for each of the three data sets are presented. Of the three data sets considered in this study, the data set with the largest amplitude fluctuations in the measured variables proves to be the least sensitive to reduced data resolution. This study also shows that flightpath-wind reconstruction is more sensitive to translational body-axis acceleration and Euler angle resolution than to air-variable resolution (angle of attack, angle of sideslip, and true airspeed).

INTRODUCTION

Measurements from digital flight data recorders are used in accident investigations for reconstructing the time histories of the flightpath winds (winds along the flightpath) and the aircraft inertial velocity. The analysis of flightpath winds following wind-shear encounters has provided valuable insight into wind-shear phenomena, which must be better understood in the interest of aircraft safety. Recently, the Federal Aviation Administration (FAA) and the National Transportation Safety Board (NTSB) recommended the installation of flight data recorders in more classes of aircraft, including the commuter and general aviation categories (ref. 1). The availability of high-technology, solid-state flight data recording equipment is one basis for this latest recommendation. Two advantages of solid state recorders over magnetic-tape recorders are that they are lighter and smaller (ref. 2). One disadvantage of the current solid state recorder is that it has a lower data storage capacity (i.e., total number of data words) than the magnetic-tape recorder.

To offset solid state memory limitations without reducing the number of stored channels or the sampling rate, the volume of data measured at a given sampling rate can be reduced by using an on-line data compression scheme. One common data compression scheme updates a measurement only if a change has occurred at the current sampling time, but this method becomes ineffective when the sensor and data resolutions are so fine that unwanted noise produces a measurement change at every sampling. The key to the effective use of this data compression technique is to choose a data resolution that is fine enough to capture the essence of the measured quantity while being coarse enough that measurement noise will not change the measurement at every sampling. Of the parameters typically recorded, translational body-axis acceleration measurements usually have the lowest signal-to-noise ratio; if they were stored with a very fine resolution, the solid state recorder would become saturated with accelerometer measurements.

The objective of this research is to examine how the choice of data resolution used in solid state flight recorders relates to the accuracy of the aircraft-state and flightpath-wind reconstruction. Determining which flight recorder variables can possess lower resolution without greatly affecting the accuracy of

aircraft-state and wind-velocity estimation makes data compression techniques more effective for the solid state recorder. The following variables are discussed in this report: the three Euler angles [pitch (θ), roll (ϕ), and yaw (ψ)], the air variables [angle of attack (α), angle of sideslip (β), and true airspeed (V)], and the translational body accelerations (a_x, a_y, a_z).

In this study, flight recorder variables adjusted to maximum nominal resolutions are used to compute nominal solutions of aircraft-inertial-velocity and flightpath-wind time histories. The resolution of each flight recorder variable is then systematically reduced, and the solutions are recomputed. The RMS error between the nominal and reduced-resolution solutions quantifies the effect of reducing the resolution of a given flight recorder variable. A flowchart of this approach is presented in figure 1. Two digital-flight-recorder data sets and one simulated data set were chosen for the sensitivity analysis.

The equations of motion used to compute the solutions for the aircraft inertial velocity and the flightpath-wind velocity are presented in the next section, followed by a description of the algorithm used to reduce the resolution of an individual data channel. The data sets used in the analysis are then described. Results are presented in the form of plots showing RMS solution error versus input channel resolution for each input channel required for the solutions. These plots are interpreted, and some concluding remarks follow.

AIRCRAFT-VELOCITY AND FLIGHTPATH-WIND-VELOCITY COMPUTATIONS

The aircraft's inertial-velocity time history can be computed given the time histories of the Euler angles (θ, ϕ, ψ) and of the translational body accelerations (a_x, a_y, a_z). First, the inertial acceleration ($\ddot{x}, \ddot{y}, \ddot{z}$) of the aircraft is computed using the transformation shown in equations (1) from body-fixed coordinates to coordinates in an inertial frame (ref. 3). The acceleration components a_x, a_y , and a_z are written with respect to the orthogonal body-fixed coordinate frame. The origin of the body-fixed frame is at the aircraft center of gravity, with the x -axis pointing through the nose, the y -axis pointing out the right wing, and the z -axis pointing down. The acceleration components \ddot{x}, \ddot{y} , and \ddot{z} are written with respect to an inertial vertical frame of reference, with the x -axis pointing north, the y -axis pointing east, and the z -axis pointing down.

$$\begin{aligned}
 \ddot{x} &= a_x \cos \theta \cos \psi + a_y (\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi) \\
 &\quad + a_z (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi) \\
 \ddot{y} &= a_x \cos \theta \sin \psi + a_y (\sin \phi \sin \theta \cos \psi + \cos \phi \cos \psi) \\
 &\quad + a_z (\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi) \\
 \ddot{z} &= (a_y \sin \phi + a_z \cos \phi) \cos \theta - a_x \sin \theta + g
 \end{aligned} \tag{1}$$

The inertial acceleration is then integrated with respect to time to obtain the inertial velocity of the aircraft. To perform this integration, the initial inertial velocity must be estimated; in this study, it was numerically selected so the solution using reduced resolution would be the best fit to the nominal solution. The integration scheme is a single-step numerical approximation to the Euler method. The inertial velocity

is evaluated as follows:

$$\begin{aligned}\dot{x}_{i+1} &= \dot{x}_i + \Delta t (\ddot{x}_{i+1} + \ddot{x}_i) / 2 \\ \dot{y}_{i+1} &= \dot{y}_i + \Delta t (\ddot{y}_{i+1} + \ddot{y}_i) / 2 \\ \dot{z}_{i+1} &= \dot{z}_i + \Delta t (\ddot{z}_{i+1} + \ddot{z}_i) / 2\end{aligned}\tag{2}$$

Flightpath-wind velocities are computed using the aircraft inertial velocities from equations (2) and the air variables (α , β , V). The following relations give the wind-velocity components, resolved in the inertial reference frame (ref. 3):

$$\begin{aligned}w_x &= \dot{x} - V \cos \psi_a \cos \gamma_a \\ w_y &= \dot{y} - V \sin \psi_a \cos \gamma_a \\ w_z &= \dot{z} - V \sin \gamma_a\end{aligned}\tag{3}$$

The wind-axis Euler angles ψ_a and γ_a used in equations (3) are defined by (ref. 3):

$$\begin{aligned}\sin \gamma_a &= \cos \alpha \cos \beta \sin \theta - (\sin \alpha \cos \beta \cos \phi + \sin \beta \sin \phi) \cos \theta \\ \tan (\psi_a - \psi) &= \frac{\sin \beta \cos \phi - \sin \alpha \cos \beta \sin \phi}{\cos \alpha \cos \beta \cos \theta + (\sin \alpha \cos \beta + \sin \beta \sin \phi) \sin \theta}\end{aligned}\tag{4}$$

DATA RESOLUTION MODIFICATION ALGORITHM

Measurements taken using a digital system such as the digital flight recorder can have only discrete values. Table 1 shows the binary words, their decimal equivalents, and their engineering values for a hypothetical 3-bit digital system. In this example, the resolution was arbitrarily chosen to be 2.0 engineering units.

Table 1. A data word and its corresponding engineering value

Binary Word	Decimal Equivalent, i	Engineering Value, $f(i)$
000	0	0.0
001	1	2.0
010	2	4.0
011	3	6.0
100	4	8.0
101	5	10.0
110	6	12.0
111	7	14.0

The decimal equivalent, i , in table 1 is related to the engineering value, $f(i)$, by

$$f(i) = f(0) + Qi \quad (5)$$

where Q is the resolution of the system. The system bias, $f(0)$, is the engineering value corresponding to the binary word equal to zero. The bias in the example given in table 1 is equal to 0.0.

In this analysis, equation (5) is used to change the resolution of a measurement time history by converting the engineering values, $f(i)$, in a measurement record to reflect the new resolution. Using the new resolution, Q , with the original values of $f(i)$ and the bias, $f(0)$, equation (5) is solved for i , and the result is rounded to the nearest integer. This value of i is then used with the new resolution and the bias to compute the new $f(i)$, again using equation (5).

Because different flight recorders use different resolutions to store data from a given channel, each channel in each data set used in this study is normalized with the same resolution. The resolutions and biases shown in table 2 are the ones used in this study for the nominal data set. The resolution values in table 2 were set arbitrarily small.

Table 2. Nominal resolution and bias

Parameter	Resolution, Q	Bias, $f(0)$
ϕ , deg	0.001	0.0
θ , deg	0.001	0.0
ψ , deg	0.001	0.0
a_x , g	0.0001	0.0
a_y , g	0.0001	0.0
a_z , g	0.0001	1.0
α , deg	0.01	0.0
β , deg	0.01	0.0
V , ft/sec	0.1	0.0

DESCRIPTION OF DATA SETS

Trajectories computed from each of the three data sets used in this study are shown in figure 2. The trajectory in figure 2(a) was computed using digital flight recorder measurements from a 747SP aircraft in cruise, using data supplied by the NTSB, from the China Airlines Incident in 1985. The trajectory in figure 2(b) is that of a simulated aircraft executing a rising coordinated turn. The trajectory in figure 2(c) was computed using digital flight recorder measurements from an L1011 aircraft as it penetrated a microburst on final approach (ref. 4).

The nominal flightpath-wind-velocity solutions for each of the three cases are shown in figure 3. The cruise case (fig. 3(a)) is characterized by a relatively long data record of 300 sec (only 150 sec are shown) and small variations in flightpath winds. The simulated rising turn (fig. 3(b)) excites all flight recorder

parameters using a steady maneuver, and produces smooth, medium-sized variations in flightpath winds. The microburst case (fig. 3(c)) shows the large wind fluctuations characteristic of a severe wind-shear encounter.

RESULTS AND DISCUSSION

The results are presented in the form of resolution sensitivity curves, shown in figures 4 through 12. Three curves, one for each data set, are plotted in each graph. The curves show RMS error in wind-velocity or aircraft-velocity components as a function of data channel resolution; the RMS error is that between the nominal wind-velocity or aircraft-inertial-velocity solution, and the reduced-resolution solution. Each plot shows the RMS error resulting from the reduced resolution of one channel only; all other channels remain at the nominal resolution shown in table 2.

Euler Angle Sensitivity

Equations (3) define the flightpath-wind velocity as the difference between the aircraft's inertial velocity and its true airspeed. Euler angle measurements affect both of these quantities, but in different ways. The inertial velocity components are affected through the body-to-inertial-axis transformations of equations (1) and the integrations of equations (2); the true airspeed components are affected through the sines and cosines on the right-hand side of equations (3). Figures 4 through 6 show the computed aircraft-inertial-velocity and wind-velocity sensitivities to pitch, roll, and yaw resolution, respectively. These curves lead to a better understanding of how the inertial-velocity and true-airspeed terms on the right side of equations (3) affect the wind-velocity estimates.

The pitch resolution sensitivity curves are shown in figure 4. The curves on the left show the sensitivity of the aircraft-inertial-velocity components to pitch resolution; the curves on the right show the sensitivity of the flightpath-wind-velocity estimates to pitch resolution. The plots show that the vertical wind-velocity (w_z) estimate is more sensitive to pitch resolution than are the other two wind-velocity components, independent of the data set. Note that the horizontal wind-velocity (w_x , w_y) sensitivity to pitch resolution is almost exclusively due to the horizontal inertial-velocity sensitivity (figs. 4(a),(b)), while the vertical wind-velocity sensitivity is almost exclusively due to true airspeed transformation sensitivity (fig. 4(f)).

Sensitivity to roll resolution has a different pattern. The similarity between the aircraft-inertial-velocity sensitivity curves (figs. 5(a)-5(c)) and the flightpath-wind-velocity sensitivity curves (figs. 5(d)-5(f)) indicates that the wind-velocity sensitivity to roll resolution is due primarily to the inertial-velocity sensitivity to roll-angle resolution. The sine and cosine functions on the right-hand side of equations (3) are affected little by a decrease in the ϕ resolution, compared to the effect that \dot{x} , \dot{y} , and \dot{z} have on the winds, through equations (1), as a result of reduced ϕ resolution. Notice that the horizontal wind-velocity estimates are more sensitive to roll resolution than is the vertical wind-velocity component; this is the opposite of the pitch resolution case.

Figure 6 shows that the aircraft inertial-velocity computation is almost completely insensitive to yaw resolution. Only the horizontal wind-velocity estimates are sensitive to yaw resolution. Like the sensitivity to roll resolution, the sensitivity of the horizontal wind-velocity estimates to yaw resolution is greater than that of the vertical wind estimate.

Body-Axis Acceleration Sensitivity

Body-axis accelerometer measurements have a direct effect on wind-velocity estimates through equations (1), but they are not used to compute the true airspeed terms in equations (3). Therefore, any sensitivity of the wind-velocity estimates to accelerometer resolution comes directly from the inertial velocity terms (\dot{x} , \dot{y} , \dot{z}) in equations (3). Figures 7 through 9 show inertial velocity sensitivity to body-axis acceleration resolution.

Figures 7 and 8 show that the computation of the horizontal aircraft-inertial-velocity components is more sensitive to the longitudinal (a_x) and lateral (a_y) acceleration resolution than is the vertical velocity computation. Figure 8 shows that for the simulated rising turn, the RMS error due to a_y resolution remains constant for a_y resolutions coarser than about 0.01 g. This is because a_y fluctuates near zero for ordinary aircraft operations, and for small fluctuations a_y is stored as a constant (zero in this case) when the data resolution is coarse.

The three components of RMS inertial velocity error versus a_z resolution are shown in figure 9. As was the case for a_y , the RMS errors due to a_z resolution may become constant with coarse resolution. Since a_z typically fluctuates near 1 g in cruise, a coarse a_z resolution may produce a constant a_z measurement of 1 g.

Air Variable Sensitivity

The sensitivities of flightpath winds to the resolution of the air variables (angle of attack, angle of sideslip, and true airspeed) are shown in figures 10 through 12. Recall that the inertial velocities (\dot{x} , \dot{y} , \dot{z}) are independent of the air variables; therefore, the flightpath-wind sensitivity to the air variables will involve only the true airspeed terms on the right side of equations (3). Figure 10 shows that the vertical wind-velocity component is much more sensitive to α resolution than are the horizontal wind-velocity components. The simulated rising-turn curve is not shown in figure 11 because $\beta = 0$ during this maneuver. Since β fluctuates near zero for the cruise case, the RMS errors in figure 11 reach a constant value for coarser resolution.

The sensitivity of flightpath winds to true airspeed resolution is shown in figure 12. Because the aircraft records in this study are from conventional flight, the horizontal components of the flightpath-wind velocity are more sensitive than the vertical component.

General Results

Wind-velocity estimates are most sensitive to the variables which are used in the inertial velocity integration, i.e., Euler angles and body accelerations. Variables measured with a coarse resolution are more likely to contain biased measurements because of quantization. A measurement bias, unlike measurement noise, has a direct effect on integration results. Wind-velocity estimates are least sensitive to the air variables, which are not used in an integration.

Low data resolution provides reasonable accuracy for wind-velocity estimates if aircraft motions are sufficiently large. The wind-shear data set contains large-amplitude variations in the measured variables,

and the sensitivity curves show the wind-velocity estimates to be least sensitive to reduced resolution. On the other hand, the sensitivity curves for the cruise case, in which aircraft motions are relatively small, show a higher sensitivity to reduced resolution. This results in larger wind-estimation inaccuracies when using coarse resolution.

Figure 13 illustrates how a coarse sensor resolution affects the measurement of high-amplitude and low-amplitude signals. Shown in the figure are examples of two signals and their corresponding measured data samples. The high-amplitude signal maintains its character when sampled, while the low-amplitude signal is stored as a constant. The sampled representations of both signals are biased because of quantization. If the signal is to be integrated, as are the Euler angles and accelerations in this study, the biased measurement will have a cumulative effect on the results; the quantization bias of the inertial acceleration, for example, causes the inertial velocity to drift from its actual value. A bias in the air variables, which are not involved in an integration, also affect the winds at each sampling time, but not in a cumulative manner.

The high-amplitude signals can acquire a quantization bias, but the bias is small relative to the signal's amplitude. With coarse resolution, the low-amplitude signal can acquire a quantization bias that is larger than the amplitude of the signal itself. It follows that integrating large-amplitude accelerations sampled with coarse resolution gives more accurate results than integrating coarsely sampled low-amplitude accelerations.

The sensitivity curves for a_y and β (figs. 8 and 11) have regions in which the RMS error becomes insensitive to increasingly coarse data resolution. The actual measurements for these results had low amplitudes with mean values that were not represented exactly in the sampled system, thus introducing the error in the wind-velocity estimation. The error did not increase with coarser resolutions because coarser resolutions did not change the sampled values. When using a coarse resolution, choosing an appropriate bias (table 2) for the data channels becomes important. It may not be possible to remove all the error with the proper choice of bias, but it is possible to remove some of the error by choosing the bias to be a nominal value, if applicable. Recommendations for nominal values for channels a_y , a_z , and β are 0 g, 1 g, and 0° , respectively.

CONCLUDING REMARKS

Curves have been presented which show the sensitivity of aircraft-inertial-velocity and flightpath-wind-velocity estimates to flight recorder data resolution. Aircraft-velocity and wind-velocity estimates were computed from flight recorder measurements of Euler angles (θ , ϕ , ψ), body-axis linear accelerations (a_x , a_y , a_z), and air variables (α , β , V). The sensitivity curves plot the RMS error between a nominal aircraft-velocity or wind-velocity solution and a reduced-resolution solution. The nominal solution uses maximum resolution on all the measured data channels. A reduced-resolution solution uses a coarser resolution on one of the input data channels. The sensitivity curves were used to quantify the effect of reduced data resolution on aircraft-inertial-velocity and wind-velocity estimates. Three data sets were considered in the analysis: a 747SP aircraft in cruise, an L1011 aircraft penetrating a microburst on final approach, and a simulated aircraft executing a rising turn.

The results show that the resolutions of the body-axis accelerations and the Euler angles have a greater effect on aircraft-inertial-velocity and flightpath-wind-velocity estimates than do the air variable resolutions. Unlike the air variables, Euler angles and accelerations are integrated when computing the solutions, so the cumulative errors caused by reducing their resolution have a greater impact on the aircraft-velocity and wind-velocity estimates.

The microburst case, which has the largest amplitude variations in the measured variables, proved to be least sensitive to data resolution reduction. This suggests that reasonable state and wind reconstruction can be attained with coarse resolution measurements if the measured variables contain large-amplitude variations.

When a coarse resolution is used, it is important that data system parameters be chosen so that the bias in equation (5) corresponds to a reasonable nominal value. The data system must have the engineering value representation of the nominal value for measurements that usually exhibit small fluctuations near a nominal value. For example, 0 g must be representable for channels such as a_y , 1 g for a_z , and 0° for β .

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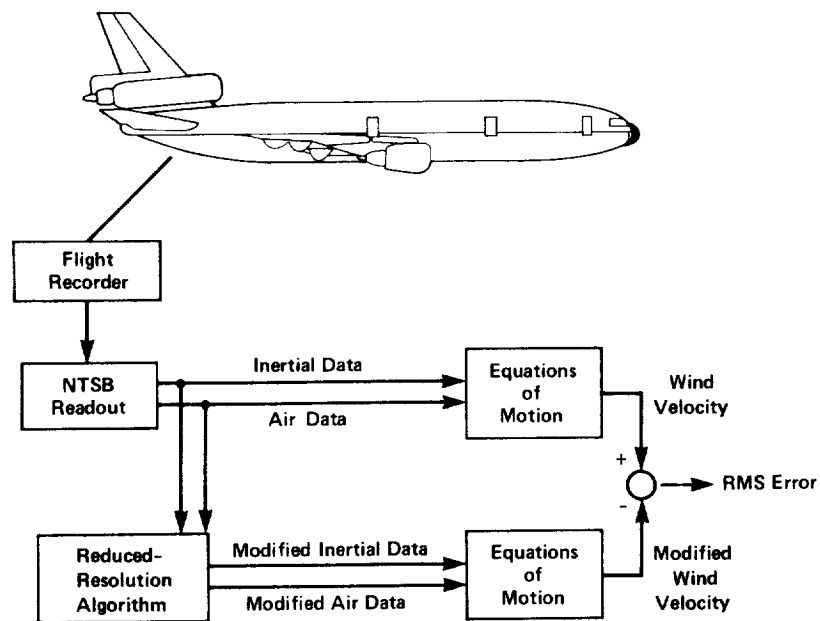


Figure 1. The data analysis algorithm.

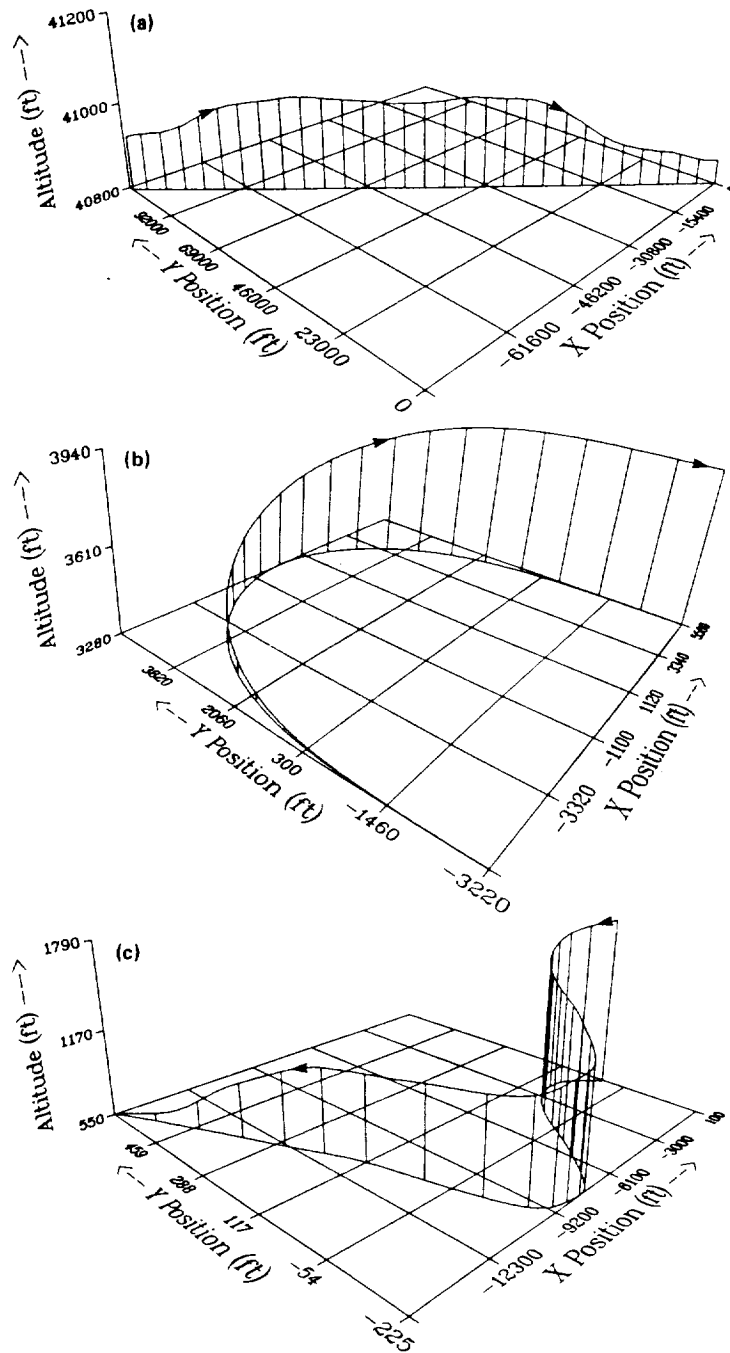


Figure 2. Trajectories for (a) 747SP in cruise condition, (b) simulated aircraft in rising coordinated turn, (c) L1011 encountering microburst on final approach.

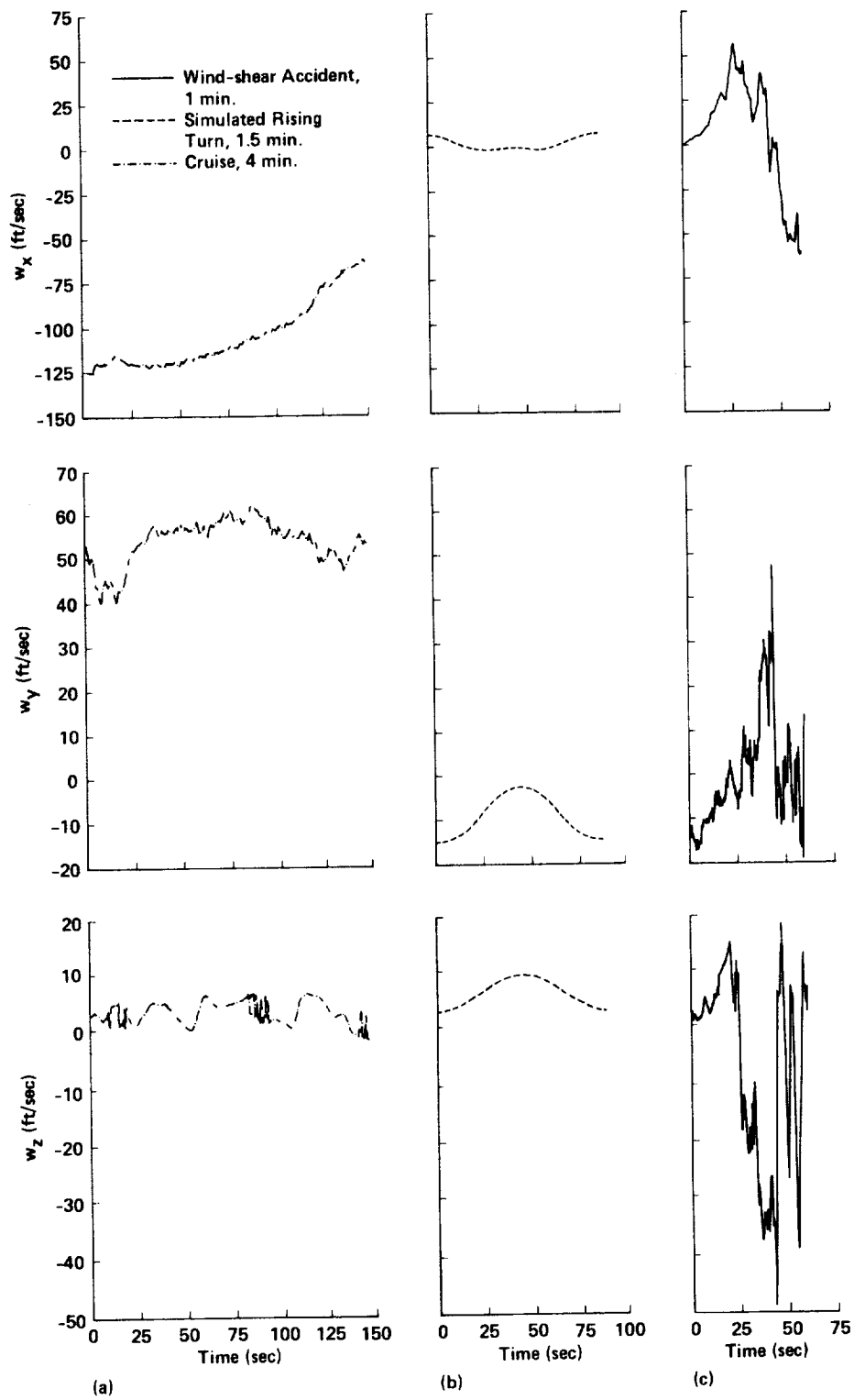


Figure 3. Flightpath-wind components for (a) 747SP in cruise condition, (b) simulated aircraft in rising coordinated turn, (c) L1011 encountering microburst on final approach.

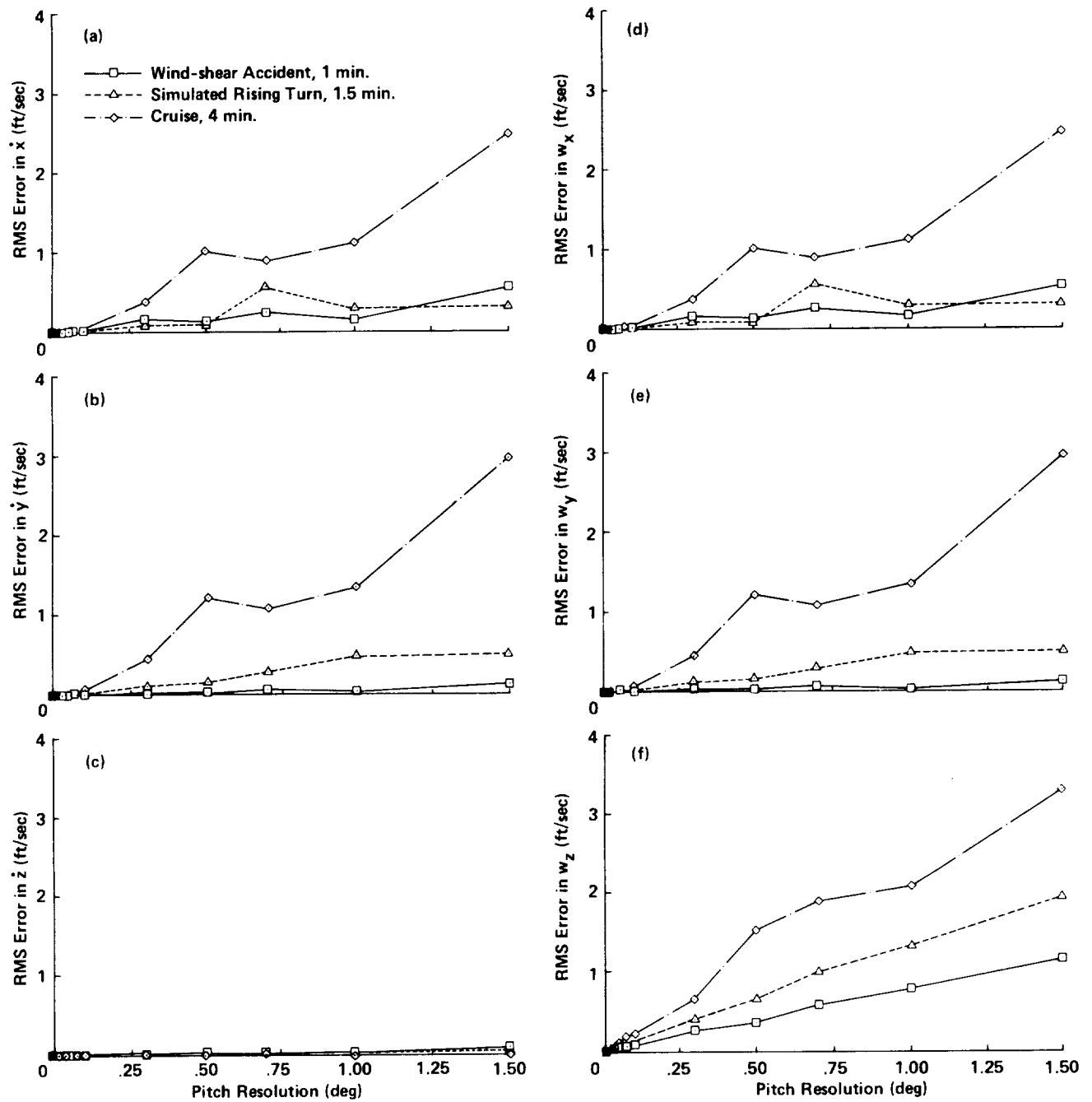


Figure 4. Sensitivity of aircraft inertial velocity (\dot{x} , \dot{y} , \dot{z}) and flightpath-wind velocity (w_x , w_y , w_z) to pitch resolution; (a) \dot{x} , (b) \dot{y} , (c) \dot{z} , (d) w_x , (e) w_y , (f) w_z .

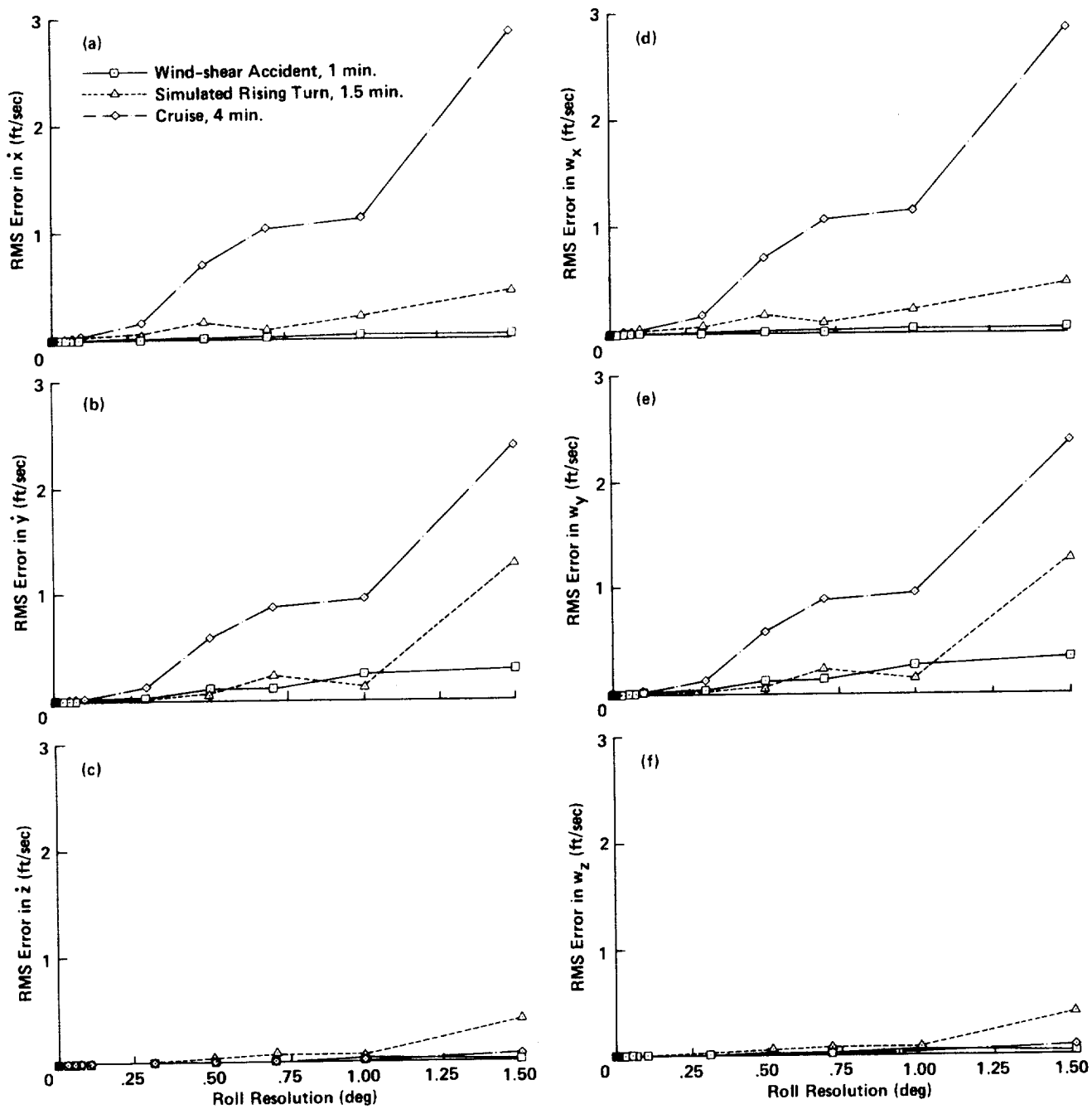


Figure 5. Sensitivity of aircraft inertial velocity (\dot{x} , \dot{y} , \dot{z}) and flightpath-wind velocity (w_x , w_y , w_z) to roll resolution; (a) \dot{x} , (b) \dot{y} , (c) \dot{z} , (d) w_x , (e) w_y , (f) w_z .

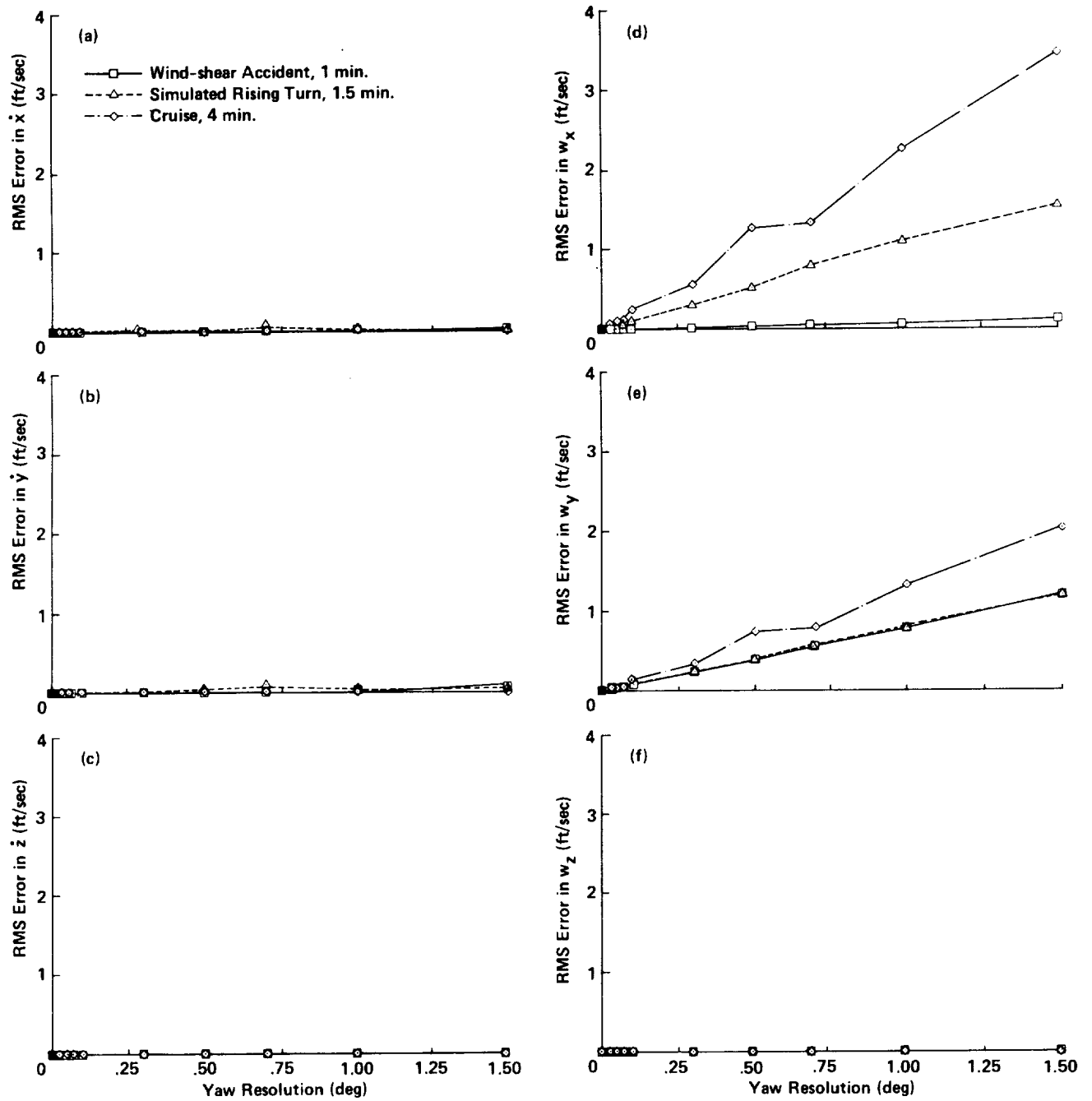


Figure 6. Sensitivity of aircraft inertial velocity ($\dot{x}, \dot{y}, \dot{z}$) and flightpath-wind velocity (w_x, w_y, w_z) to yaw resolution; (a) \dot{x} , (b) \dot{y} , (c) \dot{z} , (d) w_x , (e) w_y , (f) w_z .

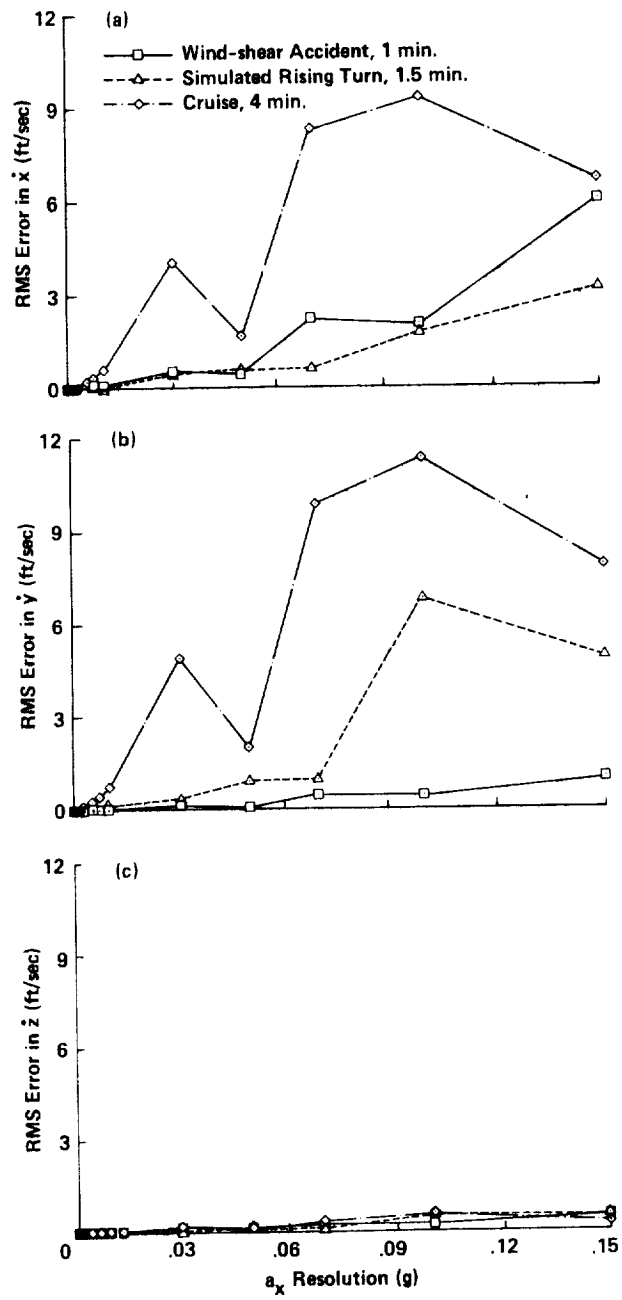


Figure 7. Sensitivity of aircraft inertial velocity (\dot{x} , \dot{y} , \dot{z}) to a_x resolution; (a) \dot{x} , (b) \dot{y} , (c) \dot{z} .

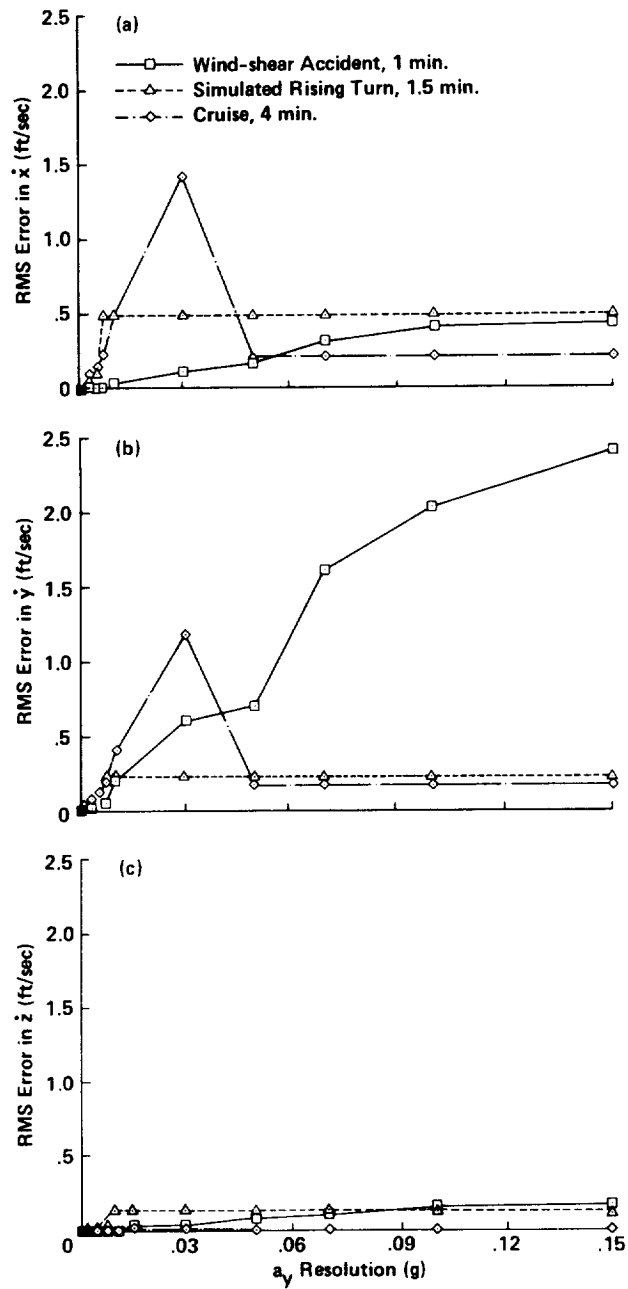


Figure 8. Sensitivity of aircraft inertial velocity (\dot{x} , \dot{y} , \dot{z}) to a_y resolution; (a) \dot{x} , (b) \dot{y} , (c) \dot{z} .

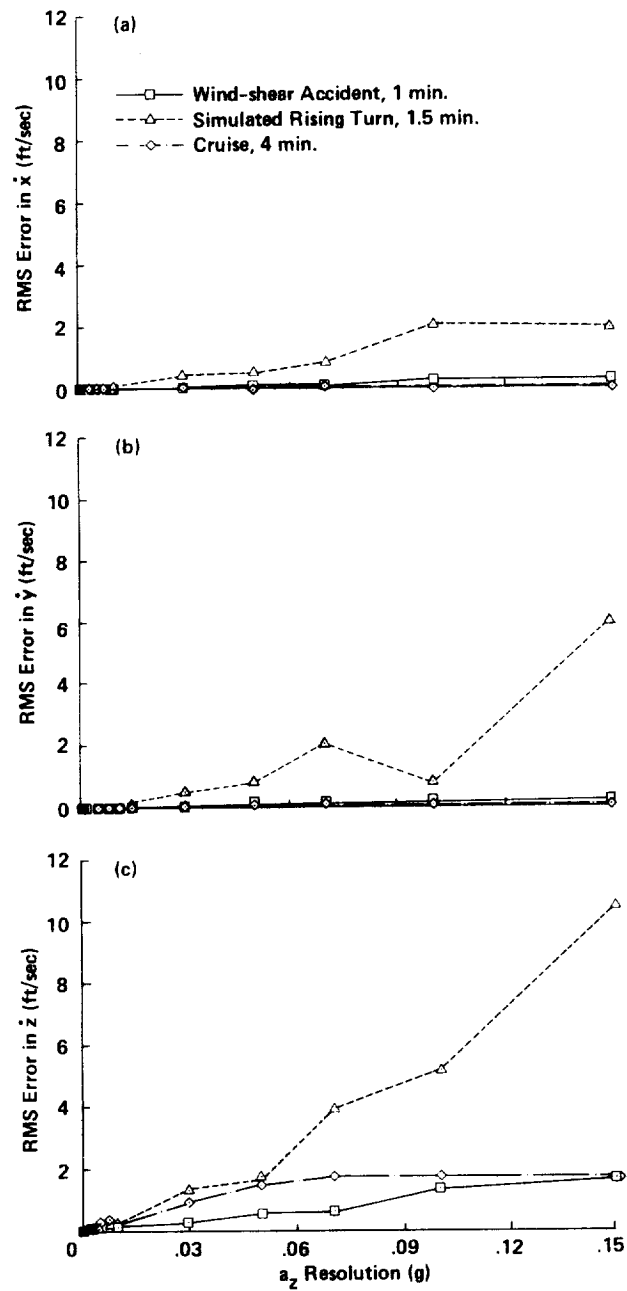


Figure 9. Sensitivity of aircraft inertial velocity (\dot{x} , \dot{y} , \dot{z}) to a_z resolution; (a) \dot{x} , (b) \dot{y} , (c) \dot{z} .

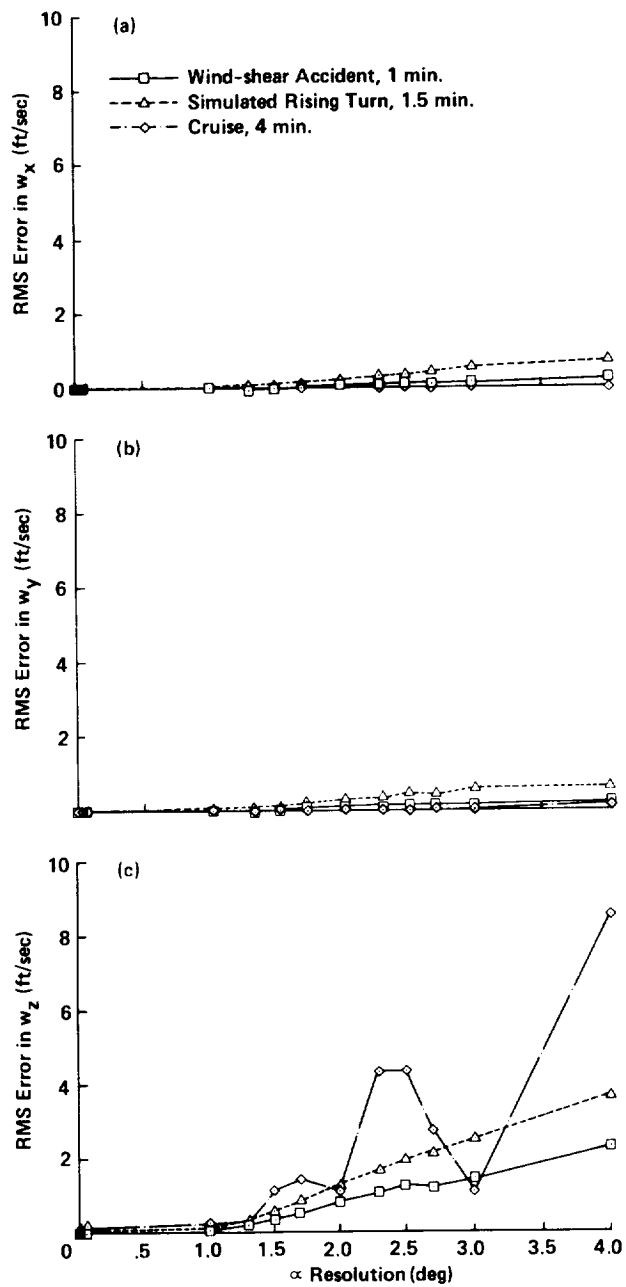


Figure 10. Sensitivity of flightpath-wind velocity (w_x , w_y , w_z) to angle-of-attack resolution; (a) w_x , (b) w_y , (c) w_z .

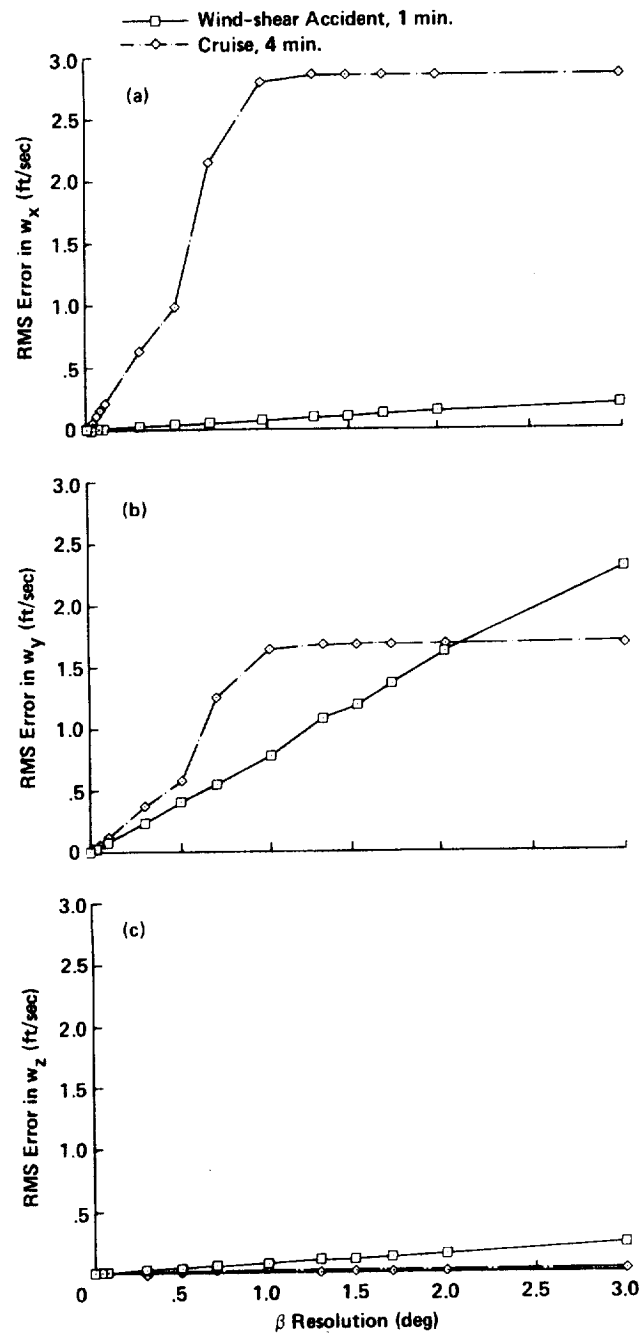


Figure 11. Sensitivity of flightpath-wind velocity (w_x , w_y , w_z) to angle-of-sideslip resolution; (a) w_x , (b) w_y , (c) w_z .

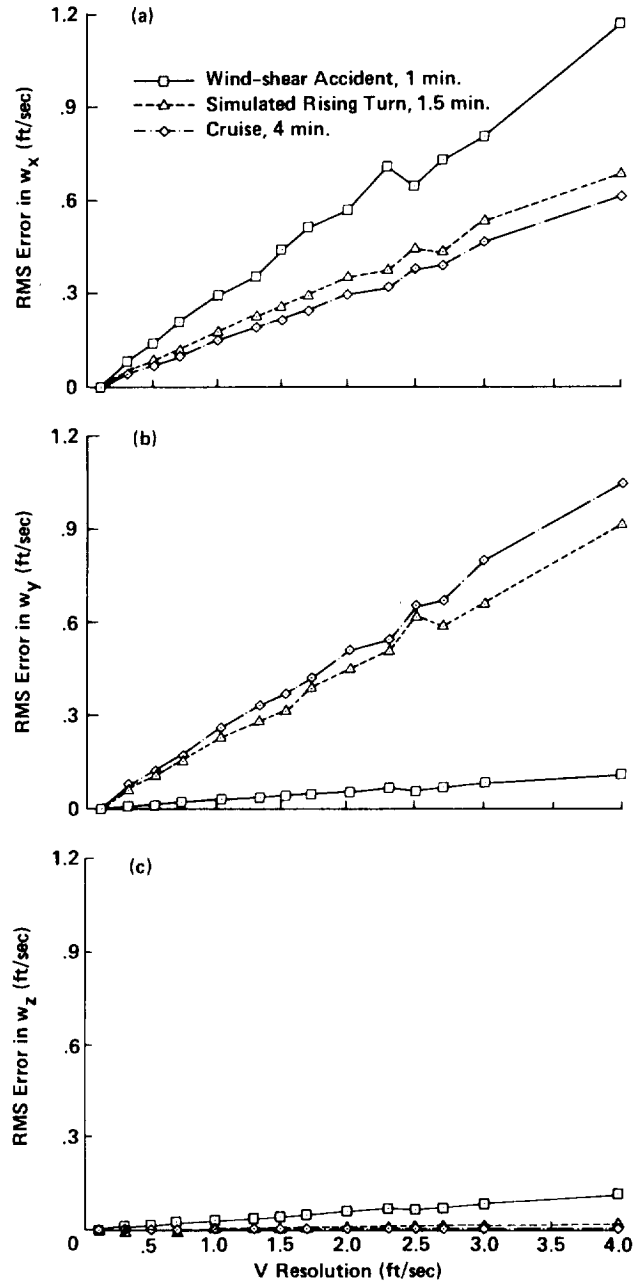


Figure 12. Sensitivity of flightpath-wind velocity (w_x , w_y , w_z) to true airspeed resolution; (a) w_x , (b) w_y , (c) w_z .

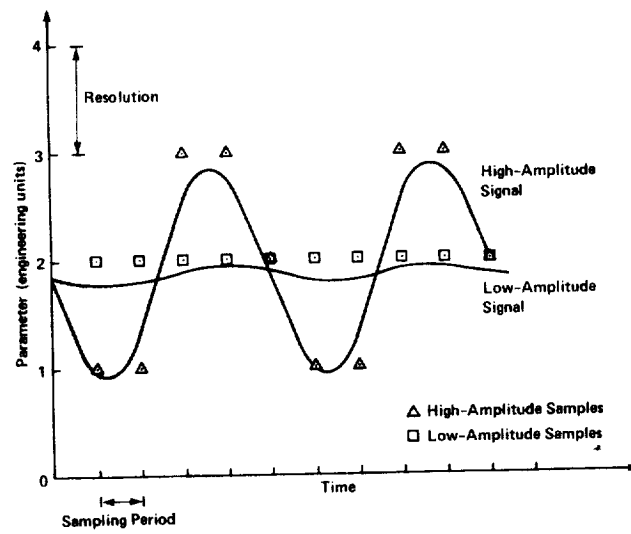


Figure 13. Illustration of the sampling bias of high-amplitude and low-amplitude signals sampled with coarse resolution.

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16. Abstract <p>This report focuses on the resolution of the digital flight data recorder measurements that are used to reconstruct time histories of the aircraft state and flightpath winds (winds along the flightpath). A sensitivity analysis is performed to determine the effects of reduced data resolution on state and wind reconstruction. Three different data sets that represent three different modes of flight are used in this analysis. Two sets are from actual digital flight data recorders; the third is simulated. Estimates of aircraft inertial velocity and flightpath-wind velocity computed from the data sets make up the nominal solutions. The resolution of each data channel used in the nominal solutions (three Euler angles, three air-data variables, and three components of translational body acceleration) is then systematically reduced and the solutions are recomputed. The RMS error between the nominal and reduced-resolution aircraft-velocity and wind-velocity solutions quantifies the effect of reduced resolution. Graphs showing RMS error versus measurement resolution for each of the three data sets are presented. Of the three data sets considered in this study, the data set with the largest amplitude fluctuations in the measured variables proves to be the least sensitive to reduced data resolution. This study also shows that flightpath-wind reconstruction is more sensitive to translational body-axis acceleration and Euler angle resolution than to air-variable resolution (angle of attack, angle of sideslip, and true airspeed).</p>					
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